Title

Guidelines for optimizing road traffic noise shielding by non-deep tree belts

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Abstract

This paper discusses that a non-deep tree belt along a road can be an interesting solution to achieve road traffic noise reduction. Noise shielding is mainly obtained as a combination of multiple scattering in the tree trunk layer and due to the presence of an acoustically soft soil. A large dataset of full-wave and highly detailed numerical simulations, based as much as possible on measured input data, shows that high biomass density should be strived for as a general rule. This conflicts, however, with practical limitations regarding access to light, nutrients and water for the trees. Some interesting approaches have been identified to relax the need for high biomass density, without affecting noise shielding to an important extent. Rectangular planting schemes, where the spacing orthogonal to the road can be increased, omitting full rows parallel to the road length axis, and thinning inside the belt are examples of such measures. It is discussed that the specific choice of a planting scheme could make a tree belt along a road an efficient noise reducing measure or not.

keywords

road traffic noise; tree belts; ecosystem services; noise pollution

1.Introduction

Since long, there has been an interest in the potential noise reduction of tree belts along roads. Such research has been based mainly on empirical work. This means that the situation “as is” is measured, so for tree belts not designed to tackle noise issues. As will be shown in the current paper, dedicated design is however needed to achieve useful noise reduction by non-deep tree belts.

Not surprisingly, many studies concluded that road traffic noise reduction by non-deep tree belts is rather limited and can hardly be considered as a relevant ecosystem service. Beranek and Ver (1976) mentioned that at least 30 m of “heavily wooded” area is needed to have relevant noise reduction (defined as “approximately 5 dBA”). A high variability by “different tree types” has been mentioned explicitly (Beranek and Ver, 1976). As a consequence, it was advised not to “ascribe attenuation of noise to wooden areas” when following the typical conservative approach in environmental impact assessments. Reynolds (1981) concluded that “if trees and bushes are used to attenuate unwanted noise, the buffer zone that is composed of them should be at least 20 meters wide and should consist of trees, ground foliage and bushes”. Kragh (1981) concluded that belts of trees and bushes (10 m to 25 m deep) produce only insignificant increases in attenuation of road traffic noise, relative to sound propagation over grass-covered or other porous ground. Mostly, the acoustically soft soil appearing below a vegetated zone has been identified as relevant (Aylor, 1972; Bucur, 2006; Cook and Van Haverbeke, 1971; Crocker, 1997; Fricke, 1984; Huisman and Attenborough, 1991; Reynolds, 1981), but the latter was not considered as a sufficiently strong argument to promote (non-deep) tree belts as a noise abatement solution (Beranek and Ver, 1976; Kragh, 1981; Reynolds, 1981).

There has been a lot of interest in the effect of leaves. It was shown that foliage is able to strongly interact with sound leading to scattering and absorption; absorption is caused by both visco-thermal effects at the leave surfaces and by damped vibrations (Martens and Michelsen, 1981; Tang et al., 1986) but only at high sound frequencies (Crocker, 1997; Kotzen and English, 2009; Kragh, 1981; Martens, 1980; Martens and Michelsen, 1981; Tang et al., 1986). As a result, it was concluded that foliage is not useful to abate road traffic noise given the limited amount of acoustic energy in the high frequency range in source spectra (Kotzen and English, 2009; Martens, 1980). Conclusions related to the foliage effect might have been generalized to vegetation belts or tree belts, and diverted attention away from the more relevant physical actors in a tree belt in relation to road traffic noise reduction, namely the ground interaction and the the presence of tree trunks.

Reynolds (1981) already wrote that "there has been considerable discussion regarding the effectiveness of vegetation in attenuating unwanted sound". More recently, Attenborough et al. (2007) refer in their book to these aforementioned typical statements in many noise control texts ("trees and hedges are not effective noise barriers"), but argue that there is increasing evidence that this is not always true. The large variety one can obtain when measuring the noise reduction at different tree belts is nicely illustrated by Fang and Ling (2003, 2005). Three excess attenuation groups have been defined (< 3 dBA, 3-6 dBA and 6-9 dBA, for belt depths of 20 m) among the 35 tree belts considered in their study.

The reported low effects measured at some tree belts and some of the aforementioned statements have lead to very conservative and thus limited effects in engineering models for outdoor sound propagation like e.g. ISO9613-2 (1996). This model forms the basis of almost any noise mapping software and is the legally prescribed calculation model in many countries and thus widely used.

The main goal of this paper is to shed a new light on the noise reducing potential of tree belts by using powerfull full-wave numerical approaches. Such sound propagation models solve the wave equations without major simplifications, giving confidence in the results. A volume discretisation approach like the finite-difference time-domain (FDTD) technique (Botteldooren, 1994), as is applied in the current study, allows studying exact positioning of trunks in a belt. This technique has become a reference solution in many fields of acoustics, including various cases where successful validation with measurements has been reported (e.g. Blumrich and Heimann, 2002; Bockstael et al., 2009; Liu and Albert, 2006; Van Renterghem and Botteldooren, 2003; Xiao and Liu, 2003). This type of analysis has become feasible only in the last decade due to the increased access to computing power.

This paper is organized as follows. The main physical actors leading to noise reduction in a tree belt are first discussed. In order to tackle realistic, multi-lane traffic noise situations, some approaches are needed to simplify this three-dimensional problem. The possibility to model sound propagation in two orthogonal planes, as illustrated and discussed in detail by Van Renterghem and Botteldooren (2012b), is quickly introduced. In a next section, the topic of validation of the numerical method in the specific area of sound propagation through tree belts is discussed. Next, a typical road traffic noise case is described in order to reveal the main parameters of tree belts with relation to noise reduction, including approaches to limit the need for high biomass density. Finally, design guidelines are summarized.

This paper does not intend to introduce new calculation methodologies or to provide additional validation, but shows what practical measures could be when designing tree belts for noise reduction along roads. To increase applicability, focus is on non-deep tree belts as they are less land-taking.

2.Literature review : Physical noise reduction by a tree belt

The different layers in a tree belt with potential impact on sound waves are the soil layer, the trunk layer and the canopy layer (leading to crown scattering). Only the soil and trunks are able to sufficiently interact with low sound frequencies, making them the major effects when looking at road traffic noise reduction.

2.1.Soil effect

The presence of the soil can lead to destructive interference between the direct contribution from source to receiver, and a ground-reflected sound path (Attenborough et al., 2007). The presence of vegetation leads to an acoustically very soft (porous) soil (Aylor, 1972; Bucur, 2006; Cook and Van Haverbeke, 1971; Crocker, 1997; Fricke, 1984; Huisman and Attenborough, 1991; Reynolds, 1981) as a consequence of plant litter and plant rooting. This results in a shift in the ground effect towards lower frequencies compared to e.g. sound propagation over (open) grassland (Huisman and Attenborough, 1991). Due to the typical source-receiver heights in road traffic applications, this ground effect mainly occurs below 1 kHz. In order to benefit from it, the specular reflection point should be located inside the vegetation belt. In traffic noise situations, with a vegetation belt close to the road, this is most often the case. This is consistent with findings reported by Cook and Van Haverbeke (1971), showing by measurements that placement of tree/vegetation belts close to the source is optimal to reduce road traffic noise.

2.2.Trunks

Tree trunks will lead to reflection, diffraction/shielding and scattering of sound.

Reflection of sound will occur at the edge of the belt, but additional reflections might come from deeper inside the vegetation belt. Reflection is considered to be of minor importance in road traffic noise applications, as such reflections are much lower in amplitude than direct sound (Wunderli and Salomons, 2009). Therefore, reflections will not lead to increased levels in a continuous road traffic stream.

At very low frequencies, sound easily diffracts around the trunks and thus does not contribute to noise reduction. At higher sound frequencies, trunks provide direct shielding.

The most relevant process at medium-low sound frequencies is multiple scattering in between the tree trunks. Multiple scattering will redirect energy away from the (direct) sound path between source and receiver. As a result, sound energy gradually decreases during transmission through the trunk layer, leading to effective noise reduction at a single receiver. If multiple scattered sound still reaches the receiver, it has travelled a longer distance and arrives with smaller intensity. Bark absorption can contribute to noise reduction due to the many interactions between sound waves and trunks, although the absorption coefficients are typically modest (Reethof et al., 1977).

2.3.Crown scattering

When both the source and receiver are located below the canopy height, scattering by crowns results in a slightly negative effect as discussed by Lyon (1977) and as recently experimentally measured in-situ by Yang et al. (2013). Part of the sound energy can be scattered downwardly leading to an increase in sound pressure level.

The crown scattering effect will be most prominent in case of higher vehicle speeds, dominated by higher sound frequencies (Sandberg and Ejsmont, 2002). Measurements behind a noise wall along a highway showed that at a sound frequency of 10 kHz, an additional amount of scattered energy of 6 dB is obtained by the presence of a single row of tall trees (Van Renterghem and Botteldooren, 2002). Below 2 kHz, effects are smaller than 1 dB (Van Renterghem and Botteldooren, 2002). As a result, the effect on total A-weighted road traffic noise as used in the current study is expected to be very limited.

3.Methodology

3.1.Modelling approach

Sound propagation through a vegetation belt has been studied in 3D before by Van Renterghem et al. (2012). This implied that both the sound source and receivers had to be placed very close to the belt to keep computational cost within reasonable limits. This methodology is computationally too demanding to be applied to realistic multi-lane road traffic noise applications as intended in the current paper. Therefore, the methodology as discussed in detail by Van Renterghem and Botteldooren (2012b) has been used. In summary, the 3D simulation space is simplified to modelling sound propagation in two orthogonal planes. In a first plane, parallel to the ground surface, scattering, diffraction/shielding and reflection by the tree trunks is calculated. In the other plane, the sound-soil interaction is predicted. The use of 2D models gives more flexibility to reach larger source-receiver distances and to resolve higher sound frequencies. Another advantage of this approach is that the most suited calculation technique can be applied in the different planes. In the first plane, the full-wave FDTD technique (Botteldooren, 1994) is necessary. To predict the sound-soil interaction, a less demanding and faster technique may be used, like e.g. the efficient Green's Function Parabolic Equation (GFPE) method (Gilbert and Di, 1993; Salomons, 1998). This technique is able to account for ground impedance discontinuities that can be relevant (Attenborough et al., 2007) as there are different successions of soft and rigid soil when sound propagates from the different road segments towards the receiver.

The major assumptions allowing this split-up in sound propagation in two orthogonal planes are the independency of the soil effect from the multiple scattering process (Aylor, 1972; Price et al., 1988; Van Renterghem et al., 2012), the limited importance of tree trunk height in typical road traffic noise applications (Van Renterghem et al., 2012), and the equivalence between a point source and coherent line source when expressing results relative to free field sound propagation (Van Renterghem et al., 2005). These assumptions have been justified before and discussed in detail by Van Renterghem and Botteldooren (2012b).

3.2.Validation

Although validation of computational approaches should be of continuing concern and conducted where possible, in the specific case of tree belt optimization for road traffic noise reduction, insurmountable practical difficulties appear, both from a spatial and temporal point of view : Only sufficiently extended tree belts make sense in road traffic noise applications, and trees take decades to develop. As current tree belts are considered to be rather inefficient (see Introduction), measuring in such cases will hardly serve for the purpose of this study.

A belt of tree trunks will be idealized by a grid of finite-impedance cylinders, with their length axes orthogonal to the ground plane. Sound propagation in such a case is a problem that can be accurately captured by a full-wave technique like FDTD. In addition, the absorbing properties of tree bark have been measured in detail before (Reethof et al., 1977), and this real-life data has been used consequently. Although there are some clear differences in bark absorption between species, a rather low and therefore conservative absorption value (for normal incidence) of 0.075 is used as discussed by Van Renterghem et al. (2012).

Forest floors and grasslands have been well characterized acoustically, based on meta-analysis of many outdoor measurements, leading to the selection of suitable models and appropriate parameters as discussed by Attenborough et al. (2011). The same ground modelling approach in FDTD as described in detail by Van Renterghem et al. (2012) has been used here, i.e. a flow resistivity of 300 $kPasm^{-2}$ and a porosity of 0.75 for grass-covered soil, and a flow resistivity of 20 $kPasm^{-2}$ and a porosity of 0.5 for forest floors.

As discussed before, the presence of trunks and the forest floor are the major effects from a physical point of view when dealing with noise reduction. The effect of leaves has not been considered in the current calculations for which sufficient reasoning has been provided in Section 2. However, downward scattering could result in a decrease in predicted effect of roughly 0.5 dBA. As this study aims at identifying the most interesting planting schemes, most likely, scattering effects would behave similarly in the various rather dense tree belts considered.

3.3.Road traffic noise case

The numerical calculations and guidelines provided in this paper are based on a practical case namely grassland along a 4-lane road to be partly replaced by a non-deep tree belt as illustrated in Fig. 1. A single receiver is considered behind the tree belt at a height of 1.5 m above the ground. Clearly, in the reference situation there are already noise benefits due to the presence of a porous soil. If the reference case would have been a rigid soil, the noise abatement by the tree belt would become enhanced due to a strongly improved ground interaction. However, since the acoustic effects of soil and above-ground biomass can be treated independently, the choice of grassland in the reference case will not influence the planting scheme guidelines presented.

Suburban road traffic is aimed at, consisting of 85 % light vehicles and 15 % heavy traffic, all driving at a constant vehicle speed of 70 km/h. Traffic is assumed to be freely flowing. All traffic is equally distributed over the 4 lanes. Traffic intensity will not influence this relative comparison as long as free flow conditions are guaranteed. Traffic composition, in contrast, is relevant as it changes the source frequency spectrum. The noise indicator of interest is total A-weighted equivalent sound pressure level, resulting from all (uncorrelated) noise sources on the road. The Harmonoise/Imagine road traffic noise power spectrum is used (Jonasson, 2007).

A stretch of road of 100 m has been modelled, while receivers are located mostly at a distance of 30 m relative to the border of the road. When studying the influence of deeper belts, a receiver distance of 50 m has been considered. The tree belt fully covers the stretch of the road considered, except for the simulations aiming at revealing the influence of belt width (along the road length axis).

4.Numerical results and discussion

4.1.Basic tree belt noise abatement behavior

4.1.1.Trunk basal area

The fraction of the ground area taken by the tree trunk cross-sections (in plan view), indicated as the *(trunk) basal area*, can be considered as the basic parameter influencing the acoustical shielding of a tree belt. With increasing basal area, the acoustical shielding increases as depicted in Fig. 2. This parameter is able to explain 58 % of the variance (R-squared) among the 209 different planting schemes numerically evaluated for a 15-m deep tree belt, assuming a linear relationship between basal area and total A-weighted road traffic noise reduction relative to an open grassland (p-value << 0.0001). A *planting scheme* is defined as a specific choice of trunk ordering, trunk spacing and trunk diameter.

Clearly, there are important modifiers. The main goal of this paper is to identify the planting schemes resulting in the largest improvements relative to this basic behavior. Although looking for optimal planting schemes makes sense at all basal areas, the choice of a specific planting scheme becomes more relevant at higher trunk basal areas.

There are some practical limitations for above-ground biomass density since one works with living material. A basal area of 1% (100 m^2/ha) is considered to be rather easily achievable with common species and maintenance based on forest research (Reineke, 1933). If higher basal areas are needed, selecting for specific species or specific types of maintenance might be needed. Such species could be e.g. *populus* or *salix*, and pollarding (cyclical removing of all branches) is one way to achieve high stem diameters in combination with a close spacing. Especially willows could be of interest, and were identified by Kuzovkina and Volk (2009) to be suited to resolve many other environmental and ecological problems. Calculations have been limited to a basal area of 2% as a rather safe upper value. Nevertheless, a few cases were evaluated beyond this limit to explore the course of noise reduction in function of basal area. Note, however, that in case of non-deep tree belts as is aimed at here, biomass density limitations could be somewhat less restrictive than for extensive forests. Scientific research on biomass density limitations in case of non-deep tree belts is lacking to the author's knowledge.

4.1.2.Tree spacing and trunk diameter

Decreasing the distance in between adjacent trees and increasing average trunk diameter increases the basal area and thus noise shielding. The relationship between road traffic noise abatement and trunk diameter is of a linear-quadratic nature as illustrated in Fig. 3. At high trunk diameters, there will be a rapid increase in the acoustical efficiency when further increasing the trunk diameter. At small trunk diameters, the efficiency is more or less linearly dependent on the diameter. The curve presented in Fig. 3 can also be considered as the evolution over time, starting from a tree belt initially consisting of (uniform) small diameters. It is then assumed that the diameters of all trees grow at an equal rate. Calculations further show that for a tree spacing larger than roughly 3 m, the main road traffic noise shielding is expected to come from the soil interaction only.

Table 1 indicates some preference for low trunk diameters in closely spaced tree belts. In case of a 0.5-m (along the road) on 1-m (normal to the road) spacing, for trunks with a diameter of 11 cm (leading to a basal area of 200 m^2/ha), including 25% randomness in stem centre location (see Section 4.3.2), a road traffic noise reduction of 8.1 dBA is predicted in case of a 15 m-deep belt. In case of trees with a diameter of 22 cm, the maximum achievable noise reduction among the configurations simulated for the same basal area is 6.0 dBA. This finding suggests that short-rotation woodlands could be useful along roads when aiming at noise reduction. However, more studies are needed on this topic to confirm this conclusion, as specific conditions and ground development (see Section 6) in such systems are not considered in the current study.

4.1.3. Depth of the tree belt

With increasing depth of the belt, orthogonal to the road length axis, noise is further reduced (see Fig. 3). However, already for non-deep (but optimized) tree belts, substantial noise reduction is possible. A more or less linear behavior between belt depth and road traffic noise reduction is found in case of a fixed receiver position behind the tree belt. It is further assumed that the belt is sufficiently wide (parallel to the road).

4.1.4.Width of the tree belt

With decreasing width of the tree belt (parallel to the road), the overall efficiency for road traffic noise shielding decreases. In case of belts of limited width, noise from a passing car will only be reduced during the time period when cars are behind the tree belt from the point of view of the receiver. When the cars become visible for the receiver (which means oblique sound paths that do not interact with the tree belt), a similar situation as in absence of the tree belt is obtained. The global effect of the tree belt is the combination of the contributions of all possible source positions along the road. Due to the nature of the decibel scale, a strong reduction for some road segments combined with a limited reduction at others will lead to a rather limited global noise abatement (relative to the reference situation). In this analysis, it is assumed that the receiver is positioned behind the tree belt, in the middle (so at an equal distance relative to the edges).

Note, however, that oblique sound paths, from sources further away from the receiver, arrive at the receiver with less energy due to geometrical spreading, atmospheric absorption and a longer interaction zone with grassland. Clearly, at some point, making the tree belt wider is not efficient anymore as becomes clearly visible from Fig. 3.

The optimal width of the belt also depends on the distance between the belt and the receiver. Receivers at close distance need much smaller belt widths compared to receivers at larger distances. Similar to guidelines as concerns the needed length of classical noise screens (Kotzen and English, 2009), the angle enclosed between the receiver and both edges of the tree belt is the decisive parameter, and should exceed roughly 160°. Numerical analysis showed that when further making the tree belt wider, road traffic noise shielding hardly increases.

4.1.5.Trunk height

Trunk height was shown to be rather unimportant in a previous study employing full 3D calculations by Van Renterghem et al. (2012). The main reason is that the noise generation sources at vehicles appear at low heights above the road surface (Jonasson, 2007; Sandberg and Ejsmont, 2002). An important condition to benefit from the shielding provided by the trunk layer is that the plane formed by the road length axis and the receiver point crosses the stem layer. Tree belts should therefore be best positioned close to the road (see also Cook and Van Haverbeke, 1971), especially if larger receiver heights are to be expected.

When the source and receiver are located below the bottom of the canopy, slightly negative effects might appear due to downward scattering as indicated before in Section 2.3. In contrast, when the plane formed by the road length axis and the receiver position crosses the canopies of the tree belt, additional positive effects are to be expected due to foliage scattering at higher sound frequencies.

4.1.6.Receiver distance

On condition that a tree belt is sufficiently wide (parallel to the road), increasing the distance between the receiver and the road (orthogonal to it) will not reduce the noise shielding efficiency. The reason for the latter is that the noise abatement is obtained during transmission through the belt.

It is interesting to compare this aspect to the working mechanism of a traditional noise wall. There, diffraction over the top edge becomes the main sound propagation path if the barrier is well designed (Kotzen and English, 2009). The larger the detour sound has to make relative to a virtual direct sound path between source and receiver, the more efficient a noise wall will be (ISO9613-2, 1996). At large distances from the wall, however, this detour will always be limited and the shielding caused by the noise wall decreases strongly. At large distance from a tree belt, in contrast, the noise abatement as observed at short distance will still be present.

In case of a finite-width belt (parallel to the road), contributions from sound paths not interacting with the belt could result in a decreased efficiency when increasing receiver distance, as explained before. The larger the distance between the receiver and the belt, the stronger the importance of such sound paths. So larger receiver distances might need wider tree belts. A similar remark can be made when designing a noise wall.

4.2.Towards optimized planting schemes

The main goal of the current section is providing guidelines in order to achieve the highest possible road traffic noise abatement while keeping the basal area as limited as possible to comply with biological limitations.

4.2.1.Rectangular schemes

The choice of a specific lattice, while keeping the number of trees per unit area constant, can result in additional shielding. Various planting schemes have been numerically studied like square, rectangular, face-centered cubic and triangular schemes (Van Renterghem et al., 2012). In rectangular schemes, the spacing along the road, and the spacing normal to the road, is different. The face-centered cubic grid uses a square lattice, with an additional tree positioned in its centre. In a triangular scheme, connecting nearest neighbors draws a grid of equilateral triangles.

Most interesting are rectangular schemes (Van Renterghem et al., 2012) when the smallest spacing is along the road length axis. This will improve the noise shielding compared to the same scheme, but rotated over 90°. Clearly, the tree density stays the same by such a rotation. Increasing the spacing normal to the road, while keeping the spacing along the road length axis fixed and small, lowers the noise shielding only to a limited degree. With increasing density in the tree belt, the influence of orientation in rectangular schemes becomes enhanced. In case of a (regular) rectangular scheme with a spacing of 1 m by 2 m, a rotation of the planting scheme over 90° can result in a difference in shielding of 1.5 dBA (see Table 1).

It can be concluded that dense rows of trees parallel to the road length axis are interesting. At the same time, the spacing in between such rows (orthogonal to the road) can be increased without significantly decreasing the noise shielding. This has the advantage that the average tree density becomes lower and such tree belts become easier to realize.

4.2.2.Pseudo-randomness

Small deviations from a perfectly ordered positioning of trees, following a particular grid, could lead to an increase in noise shielding as initiated by the calculations by Van Renterghem et al. (2012).

The numerical simulations summarized in Fig. 4 show that the optimal degree of randomness is near 20 % of the spacing in case of a 1-m (parallel to the road) on 2-m (normal to the road) rectangular scheme with uniform stem diameters of 22 cm. This means that each tree is moved from its regular position, and placed randomly in the zone equal to 1/5th of the distance in between the trees. These shifts are introduced both along and normal to the road length axis. Very small random displacements already give an increase in shielding relative to fully regular schemes. The curve in Fig. 4 shows a rather broad maximum near 10 % - 25 %. Fully random placement, while using the same number of trees per unit area, gives more shielding than fully ordered schemes with the same basal area. However, there is a slight preference for small disturbances. A possible reason for the positive effect of small displacements is that periodicity effects, although not very pronounced, are still present, while (negative) focusing effects (Yang et al., 2004) disappear.

Clearly, since randomness in involved, different realizations do not yield exactly the same tree grids and lead to variation in the noise shielding. This variation is illustrated by the error bars in Fig. 4, having a total length of two times the standard deviation. Differences up to 0.5 dBA are found between the different realizations for a given degree of randomness.

Note that when the trunk basal area is increased, the effect of including pseudo-randomness, relative to fully ordered schemes, is strongly enhanced. This becomes clear e.g. while optimizing tree stands with diameters of 11 cm at the maximum basal area considered in this study (see Table 1).

Randomness in trunk diameter is another way to increase noise shielding. In the calculations, a normal distribution is assumed with a standard deviation for the radius equal to 5 cm (variations have been calculated for planting schemes with trunk radii of 11 cm). Although the effect of slightly disordered trunk centre locations is predicted to be somewhat stronger, the presence of stem diameter variations also slightly increase noise shielding. However, there are no additional positive effects of applying both randomness in stem positioning and diameter.

Allowing for a small degree of randomness in both stem centre location and stem diameter is also interesting from a practical point of view, and is likely to occur by nature. However, keeping control of the deviations could be relevant in the viewpoint of further optimizing noise shielding.

4.2.3.Gaps

Omitting trees from a structured tree belt is a drastic measure to reduce the (average) basal area. Numerical predictions show that such actions do not necessarily mean that the noise shielding would strongly decrease. The presence of gaps could introduce some periodicity at other sound frequencies when compared to a fully populated grid, and could compensate to some extent for the loss in basal area. This specific phenomenon of deliberately introducing holes/gaps in sonic crystals has been studied before (Garcia-Raffi et al., 2009; Romero-Garcia et al., 2009).

Omitting full rows of trees, parallel to the road length axis, will affect the acoustical shielding to a limited extent only. It is assumed that near these left-out rows in the belt, the soft forest floor still develops. The first and last row should be preferably left unaltered to avoid reducing the zone were a forest floor could develop, and to avoid limiting the actual depth of the belt. The effect of different combinations of leaving out 2 rows from originally 8 rows (see Fig. 5) is summarized in Table 1. Reducing the basal area with 25 % results in a modest acoustical loss of 0.3 dBA to 0.7 dBA, relative to a fully populated rectangular scheme at a basal area of 2 %.

Omitting full rows of trees, normal to the road, is usually not a good option. Such an action will negatively affect the noise shielding by the belt since channels will be formed allowing the noise to propagate almost undisturbed from specific positions on the road towards a receiver. Depending on the location of these channels, the noise abatement can be strongly reduced relative to a fully populated tree belt. As discussed before, unshielded parts of the road could become dominant for the total noise exposure.

Omitting at random trees within the belt slightly lowers the noise shielding. Thinning of not well developing trees after planting should therefore not be a problem from the viewpoint of noise reduction, of course within reasonable limits. Such an operation could be especially needed after planting rather dense tree belts which should be strived for - as a general rule - to abate road traffic noise. The effect on road traffic noise insertion loss of increasingly removing trees, in a fully random way, from an originally regular and fully populated belt, is illustrated in Fig. 6. In this configuration, removing up to 25 % of the trees hardly affects the noise reduction. It is assumed in these calculations that the forest floor effect is preserved, even when a large fraction of the trees were omitted.

Based on these findings, trees planted in densely positioned rows, followed by open spaces, could therefore be a practical solution (see Fig. 5 a). A 1-m (along the road) on 2-m (normal to the road) spacing in case of 22-cm diameter trunks, organized as two-by-two rows, followed by a 4-m open space, including optimal pseudo-randomness (25 %), results in 5.8 dBA road traffic noise abatement and a basal area of 1.5 % (15-m deep tree belt). Omitting at random single trees from the belt (and not full rows), will not systematically increase the available space for each tree.

5.Conclusions

The major parameters governing road traffic noise reduction by finite-depth tree belts are identified by means of detailed full-wave calculations with validated models and validated assumptions. It is discussed that mainly the presence of trunks and the forest floor interaction leads to physical road traffic noise reduction. As a general rule, high biomass density should be strived for, which can be achieved by limiting the spacing in between trees and by increasing the trunk diameter. While a linear relationship between noise shielding and belt depth (orthogonal to the road) is predicted, increasing the length of the belt (along the road) leads to convergence in the noise reduction at a single receiver positioned behind the belt. Introducing some randomness in stem centre location or trunk diameter, which is most likely to occur by nature, is positive for noise reduction. Tree height is generally not a decisive parameter on condition that the belt borders the road. In contrast to a common noise wall, moving receivers further away from the road will not decrease the tree belt performance, although wider tree belts might be needed as a larger stretch of the road then contributes. Optimized and closely packed low-diameter trunks could yield some higher road traffic noise reductions than thicker trees at the same basal area.

The need for high biomass density conflicts with practical limitations regarding biological access to light, nutrients and water for the trees. Some interesting approaches have been identified to relax the need for high biomass density, without affecting noise shielding to an important extent. Rectangular planting schemes, where the spacing orthogonal to the road can be increased, omitting full rows parallel to the road length axis, and randomly omitting trees (thinning) inside the belt are examples of such measures. Densely positioned paired rows parallel to the road length axis, followed by open spaces, could be a practical and efficient solution. The design guidelines have been schematically summarized in Figs. 7 and 8.

6.Final discussion and limitations

The results from this study indicate that tree belts along roads could be interesting to abate road traffic noise if the higher range of trunk basal areas could be achieved. The reductions presented here should be seen in the view of other propagation related measures like e.g. noise walls. Previous calculations (Van Renterghem et al., 2012, 2013) showed that an optimized 15-m deep tree belt (basal area < 0.02) could give a similar road traffic noise reduction as a classical thin and rigid noise wall, positioned at the edge of the road (the border of the tree belt), having a screen height in between 1 m and 2 m. A 30-m deep tree belt (basal area < 0.02) gives a similar performance in total A-weighted road traffic noise level as a screen with a height in between 2 m and 3 m (Van Renterghem et al., 2013). It was further shown that in case of sound propagation over rigid ground in the reference case, this equivalent screen height is typically 1 m higher in such a comparison (Van Renterghem et al., 2013).

Meteorological effects are not included in the current study aiming primarily at identifying interesting planting schemes for noise reduction. Especially near noise walls, downwind sound propagation could be detrimental for the shielding efficiency (Barriere and Gabillet, 1999; De Jong and Stusnick, 1976; Rasmussen and Arranz, 1998; Salomons, 1999), mainly due to the build-up of large vertical gradients in the horizontal component of the wind speed near the top of the wall. A possible solution, as proposed before, is the use of a row of trees behind a noise wall (Van Renterghem et al., 2002; Van Renterghem and Botteldooren, 2002, 2003) acting as a windbreak. In this respect, wind effects near tree belts are expected to be rather limited and this could be an additional benefit. Another natural solution is applying an earth berm, which was shown to be less sensitive to the aforementioned (down)wind effect (Van Renterghem and Booteldooren, 2012a).

The air temperature lapse above a forest could be quite different compared to the one above an open grassland (Huisman and Attenborough, 1991; Raynor, 1971). Changes in the refractive state of the atmospheric surface layer could influence sound propagation to an important extent (Attenborough et al., 2007; Beranek and Ver, 1976; Crocker, 1997; Reynolds, 1981), the more road traffic noise is generated very close to the earth’s surface (ISO9613-2,1996). Most likely, such effect are of special interest at deeper tree belts/forests only.

In addition, tree belts are predicted to have a high benefit-cost ratio in economic analyses focusing on noise exposure (Klaeboe et al., 2014): Tree belts have a low installation cost, are a long-lasting solution and offer at the same time reasonable noise reduction.

This numerical study indicates that noise reduction could be an additional ecosystem service of a tree belt or strip of forest. Brown and Fischer (2009) argue that the benefits of trees outside woods have been typically undervalued. General ecosystem services of tree zones (Elmqvist et al., 2013) are carbon sequestration, habitat creation and increasing biodiversity, erosion control and water runoff mitigation, wood and food production, improving microclimatology and global climate regulation, enhancing liveability and health of citizens, and so on. However, more inclusive studies are needed to identify potential conflicts or synergies arising from the design guidelines solely based on noise abatement as proposed in this work.

The guidelines in the current paper are based on numerical modelling. Although the models and the modelling assumptions have been validated where possible, and input parameters are based on measurements as much as possible, real-life implementations could be still of interest to exclude influences that might have been neglected or idealizations made in the modelling approaches. To some extent, a comparison is possible with reported measurements by Tanaka et al. (1979) (and summarized by Bucur, 2006). In contrast to many other studies, the basal areas have been measured and reported. Basal areas up to about 70 m^2/ha (0.07) were present in their dataset, giving attenuations ranging from 0 dB to 4 dB (only integer numbers were presented), at propagation distances of 10 m and 20 m relative to the forest edge. This corresponds with the predicted range in the scatter plot (Fig. 2) at low basal areas.

Any time evolution with regards to the acoustical effect of forest floors is neglected in the current study. Most likely, the transition from open grassland to a forest floor will take some time. Therefore, this acoustical benefit will not be present directly after planting a tree belt. Scientific information on this topic is however lacking. Similarly, the influence of the moisture content of forest floors is neglected, potentially limiting the soil effect when pores become water-saturated (Cramond and Don, 1987). It is further assumed that the forest floor is uncompacted; this is the optimal condition not only for noise reduction but also for its other ecological functions. Means to ecologically restore forest soils were experimentally assessed by Ampoorter et al. (2011).

In the current study, focus is on non-deep tree belts as they have a wide applicability in both suburban and urban environments due to their limited land take. A possible application is e.g. bordering an urban park along a road with an optimized tree belt. However, the guidelines presented in this paper are expected to be applicable to deeper tree belts as well. In the latter, the need for large biomass density could be relaxed as it could be compensated by a longer interaction path with the acoustically soft forest floor. Meteorological effect should then be included in the analysis.

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FIGURE CAPTIONS

Fig. 1. Reference and abatement case considered for the numerical predictions. *D* indicates the depth of the tree belt (orthogonal to the road length axis), *W* the width (parallel to the road), and *d* is the diameter of the individual trees.

Fig. 2. Scatter plot between basal area and road traffic noise insertion loss (IL, relative to grassland) of a 15-m deep tree belt bordering a 4-lane road at a receiver behind the belt (at a height of 1.5 m). Each marker stands for a particular planting scheme. The size of the symbols is proportional to the diameter of the trunks modelled (ranging from 4 cm to 28 cm). The filled symbols represent fully populated tree belts, the open symbols are used when a fraction of the trees have been omitted. Different ordering have been considered : square grids (circles), rectangular grids (squares), triangular grids (triangles), and face-centered square lattices (pentagrams). The black symbols indicate fully regularly positioned tree trunks, the grey symbols are used when randomness in tree centre location is involved. In case randomness in tree diameter is considered, a dot is placed inside the symbol. The different random realizations of specific planting schemes are presented as well. Following traffic parameters were used : 15 % heavy vehicles, all driving at 70 km/h, equally distributed over the 4 lanes.

Fig. 3. Road traffic noise insertion loss (IL, relative to grassland) in function of depth (a), width (b) and (uniform) stem diameter (c) of a tree belt. The planting scheme used is a rectangular

scheme (1-m spacing along the road length axis, 2 m orthogonal to it). Random displacements from the regular grid were allowed at 25% of the spacing in both directions. In (a) and (b), a (uniform) tree diameter of 22 cm is chosen. In (a) and (c), the tree belt was fully covering the stretch of road considered (i.e. 100 m). In (b) and (c), the depth of the tree belt was 15 m. Receivers are located at 40 m from the border of the road in (a), at 30 m in (b) and at 50 m in (c). The receiver height was 1.5 m in all cases. Following traffic parameters were used : 15 % heavy vehicles, all driving at 70 km/h, equally distributed over the 4 lanes.

Fig. 4. Road traffic noise insertion loss (IL, relative to grassland) in function of increasingly allowing randomness in stem centre location. The increasing degree of randomness departs from a (perfectly) ordered rectangular scheme with a spacing of 1 m along the road and 2 m orthogonal to it, with (uniform) stem diameters of 22 cm (=0 % randomness). The receiver is located at 40 m from the border of the road, behind a 15-m deep tree belt, at a receiver height of 1.5 m. In case neighboring trees would intersect after random placement, a new random number was generated. The errorbars are equal to two times the standard deviation as a result of 3 random realizations. Following traffic parameters were used : 15 % heavy vehicles, all driving at 70 km/h, equally distributed over the 4 lanes.

Fig. 5. The different ways of removing 2 rows (parallel to the road) out of 8 considered in case of a 1-m on 2-m spacing at a 15-m wide tree belt bordering a road.

Fig. 6. Road traffic noise insertion loss (IL, relative to grassland) in function of increasingly thinning the tree belt (in a random way). The scheme at 0% is a fully populated rectangular one, with a spacing of 1 m along the road length axis and 2 m normal to it. The (uniform) stem diameter is 22 cm. The receiver is located at 40 m from the border of the road, behind a 15-m deep tree belt, at a receiver height of 1.5 m. The errorbars have a length of two times the standard deviation and are the results of 3 (random) realizations for a given thinning percentage. Following traffic parameters were used : 15 % heavy vehicles, all driving at 70 km/h, equally distributed over the 4 lanes.

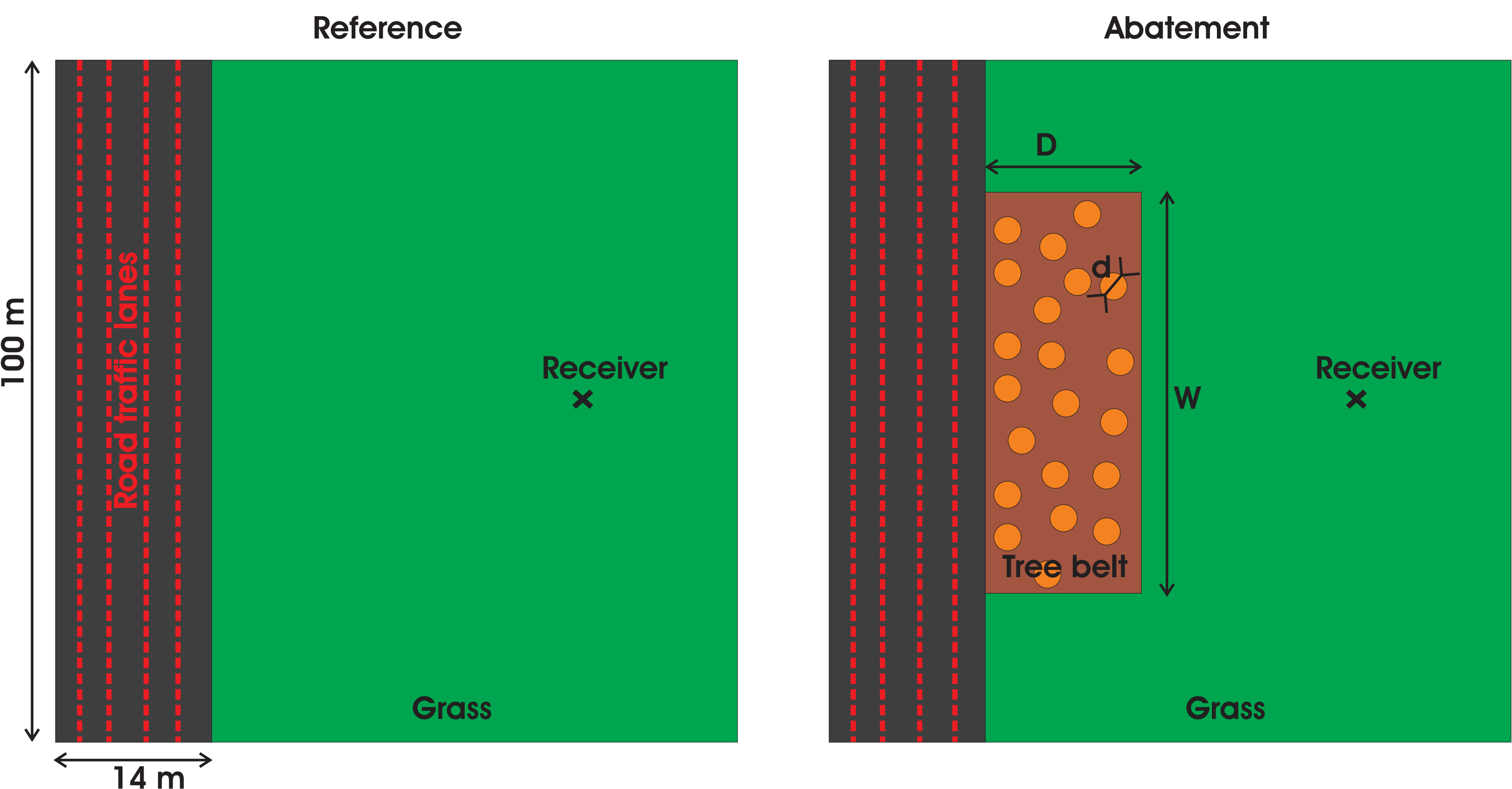
Fig. 7. Basic actions to increase road traffic noise shielding by a tree belt bordering a road.

Fig. 8. Useful actions to decrease the average basal area of a tree belt, without significantly lowering the road traffic noise shielding.

Table caption

Table 1. Selection of calculated road traffic noise insertion losses (relative to grassland) for 15-m deep tree belts using rectangular or square planting schemes (=$IL_{regular}$). Spacing *x* is the distance in between the centres of the trunks along the road length axis, spacing *y* is the spacing orthogonal to the road. Pseudo-randomness indicates random shifts in trunk location of at maximum 25 % of the spacing (=IL_{random}). When randomness is involved, the linear average over 3 repetitions is given; the standard deviation has been added in between brackets. Only cases with uniform trunk diameters are considered in this table. The receiver is located at 30 m from the border of the road at a height of 1.5 m. Following traffic parameters were used : 15 % heavy vehicles, all driving at 70 km/h, equally distributed over the 4 lanes. Crown scattering has been neglected. Superscript * means that 25 % of the trees have been omitted (in a random way); the meaning of superscripts a to g can be found in Fig. 5.

Figure 1



Reference
Abatement
100 m
Road traffic lanes
Receiver
Grass
14 m
D
d
W
Tree belt
Receiver
Grass

Figure 2

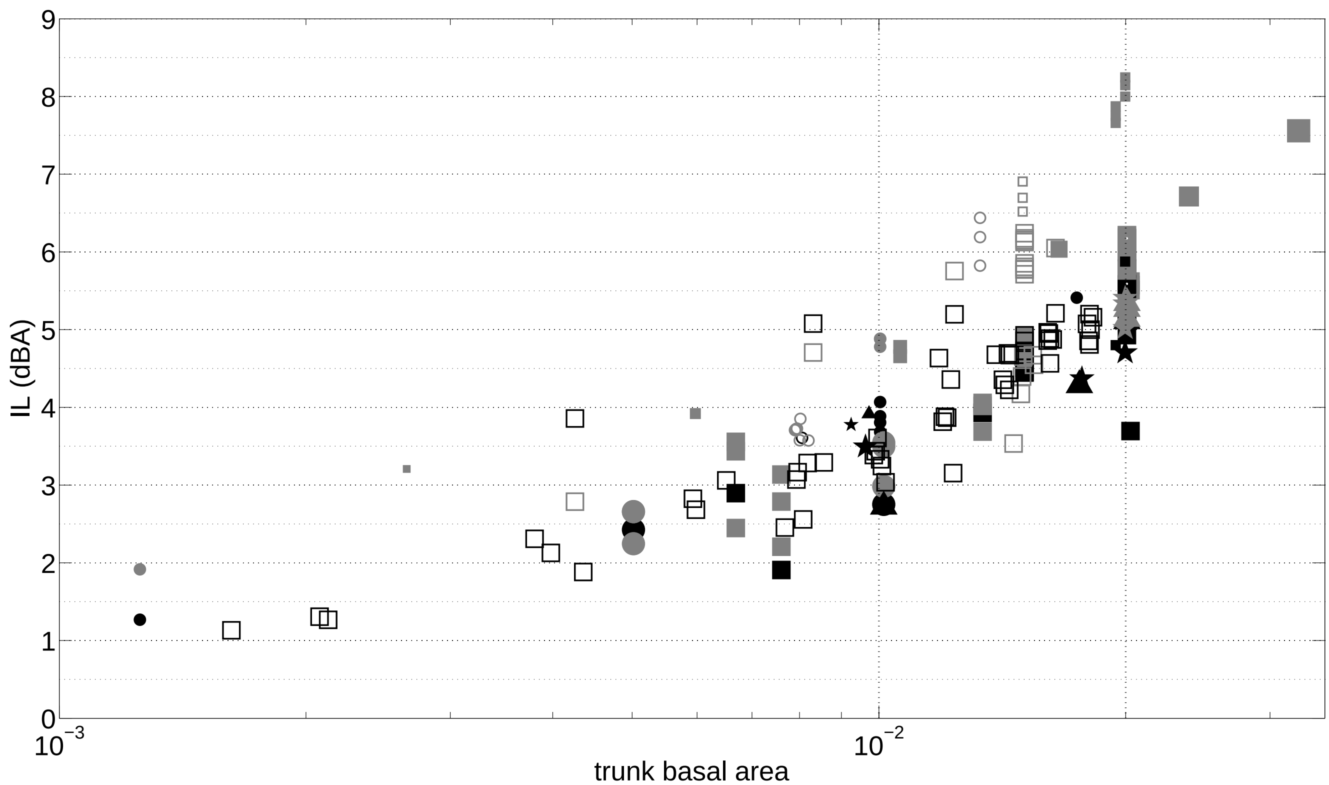


Figure 3

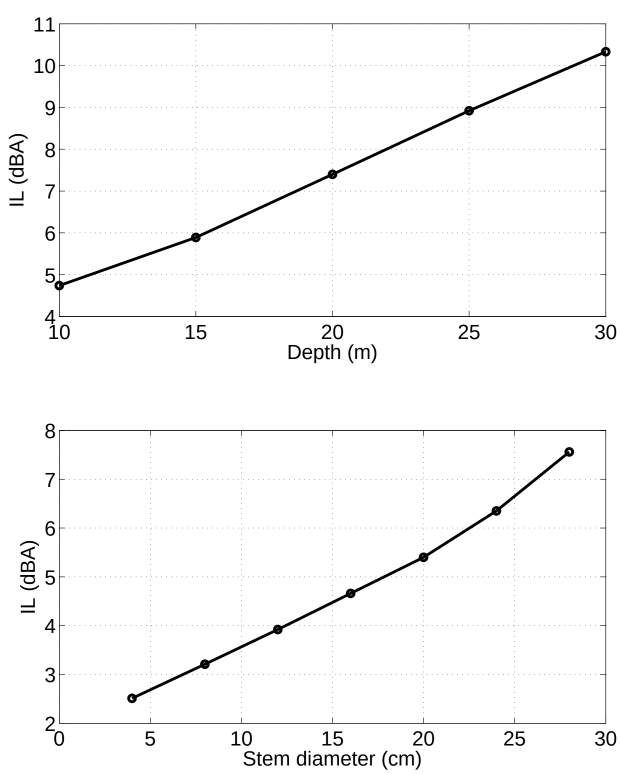


Figure 4

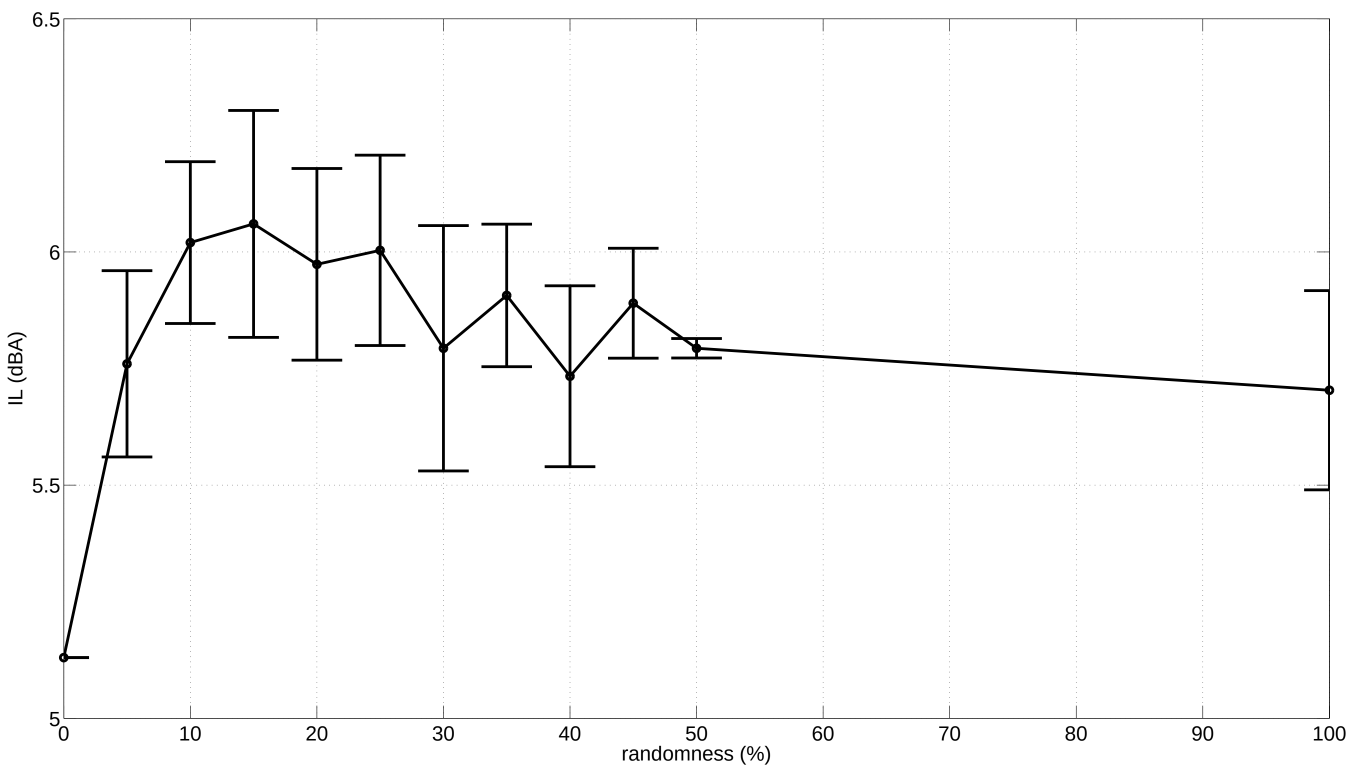


Figure 5

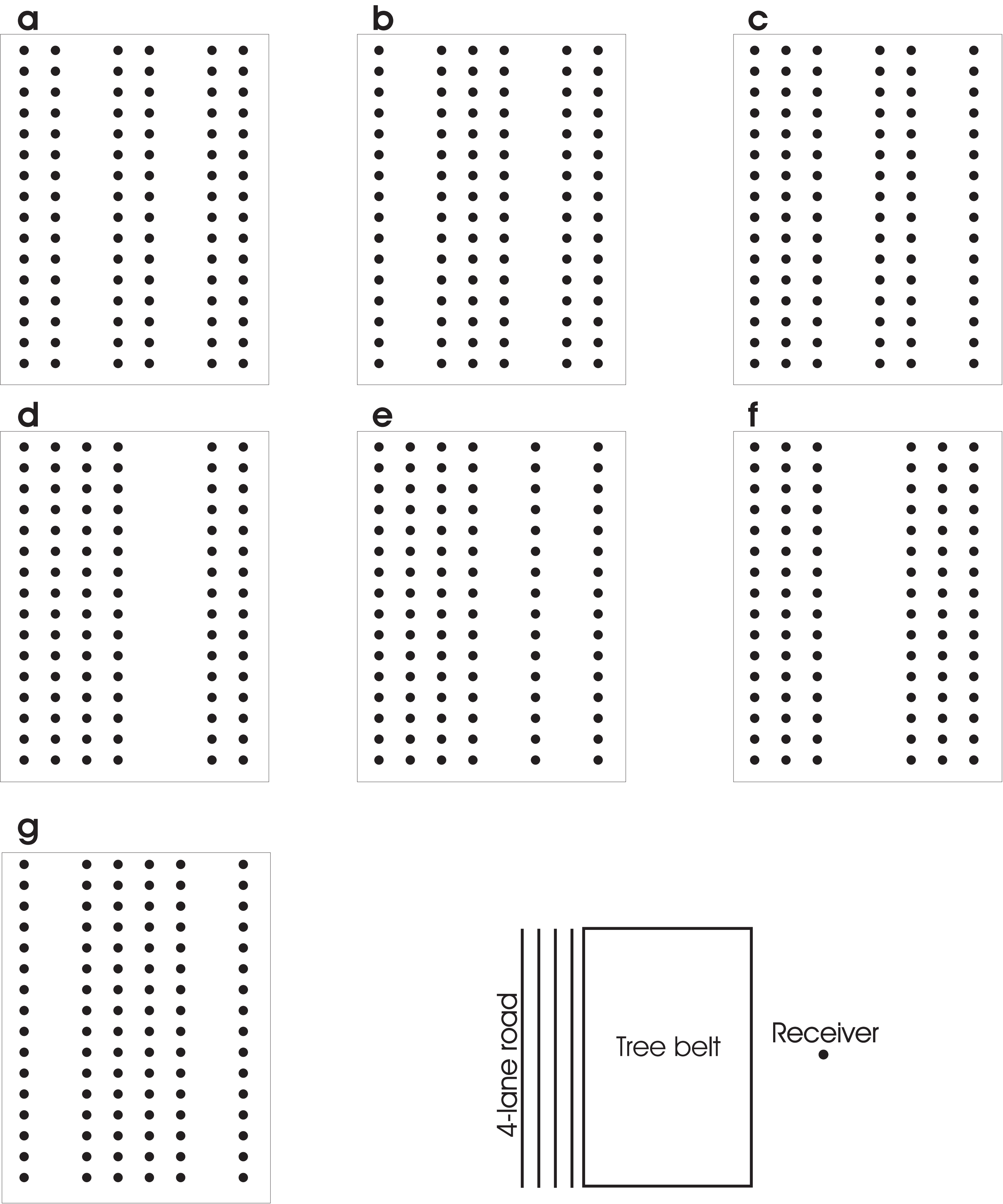


Figure 6

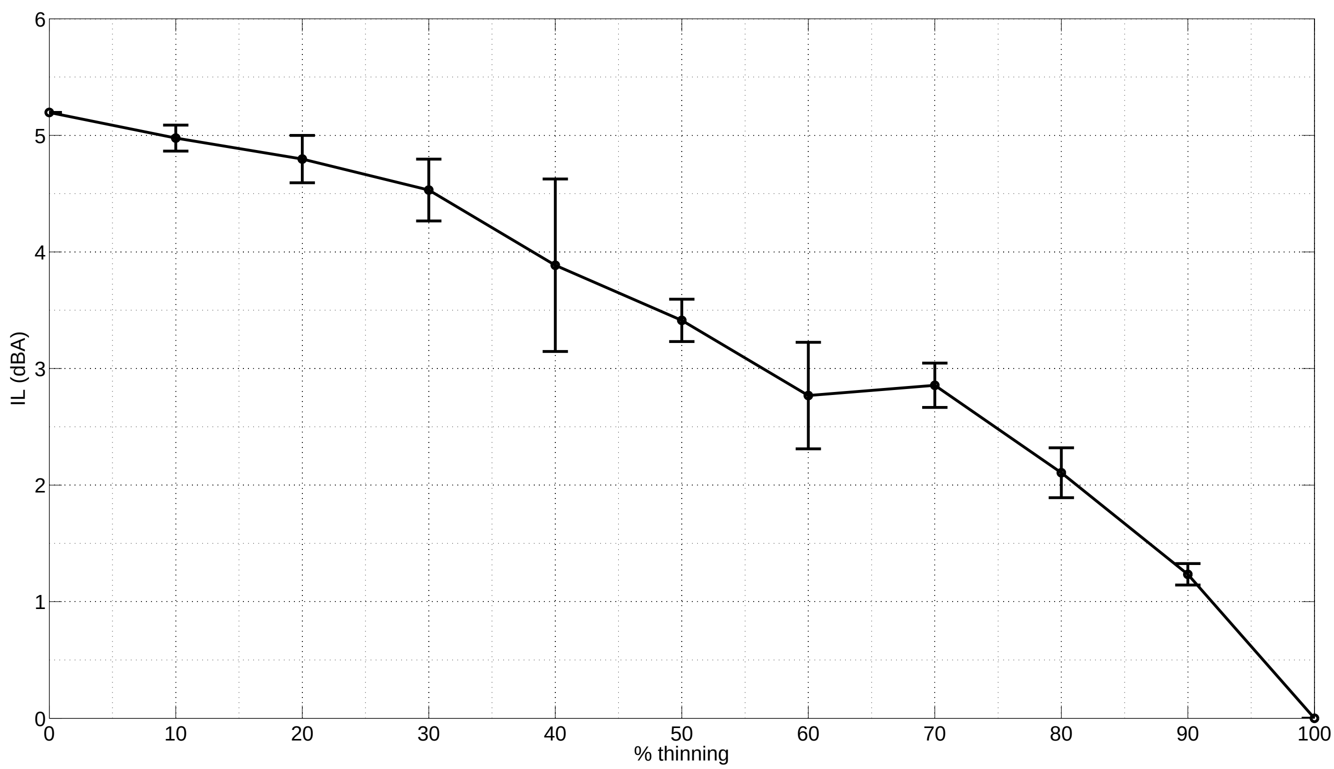


Figure 7

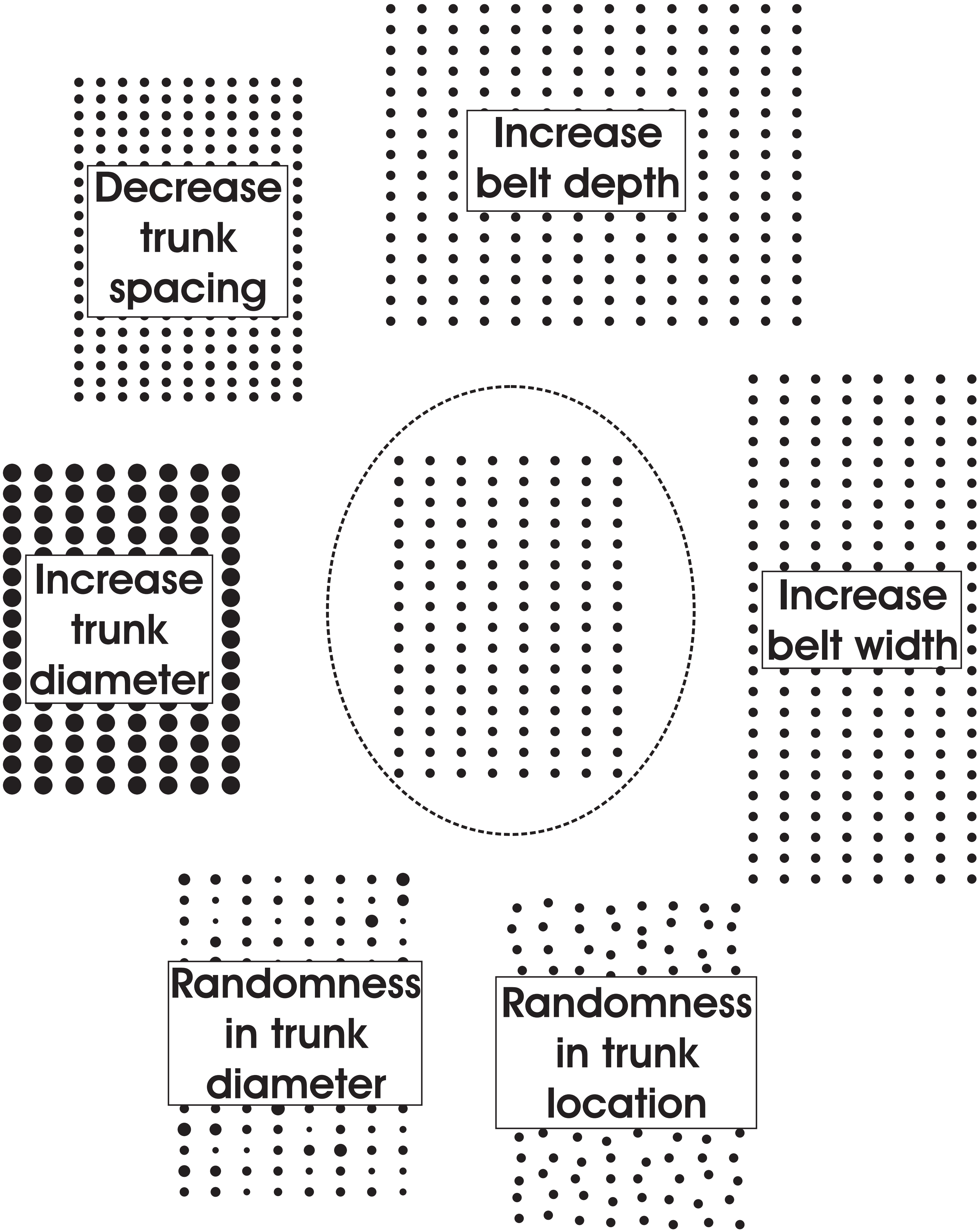

Decrease trunk spacing
Increase belt depth
Increase trunk diameter
Increase belt width
Randomness in trunk diameter
Randomness in trunk location

Figure 8

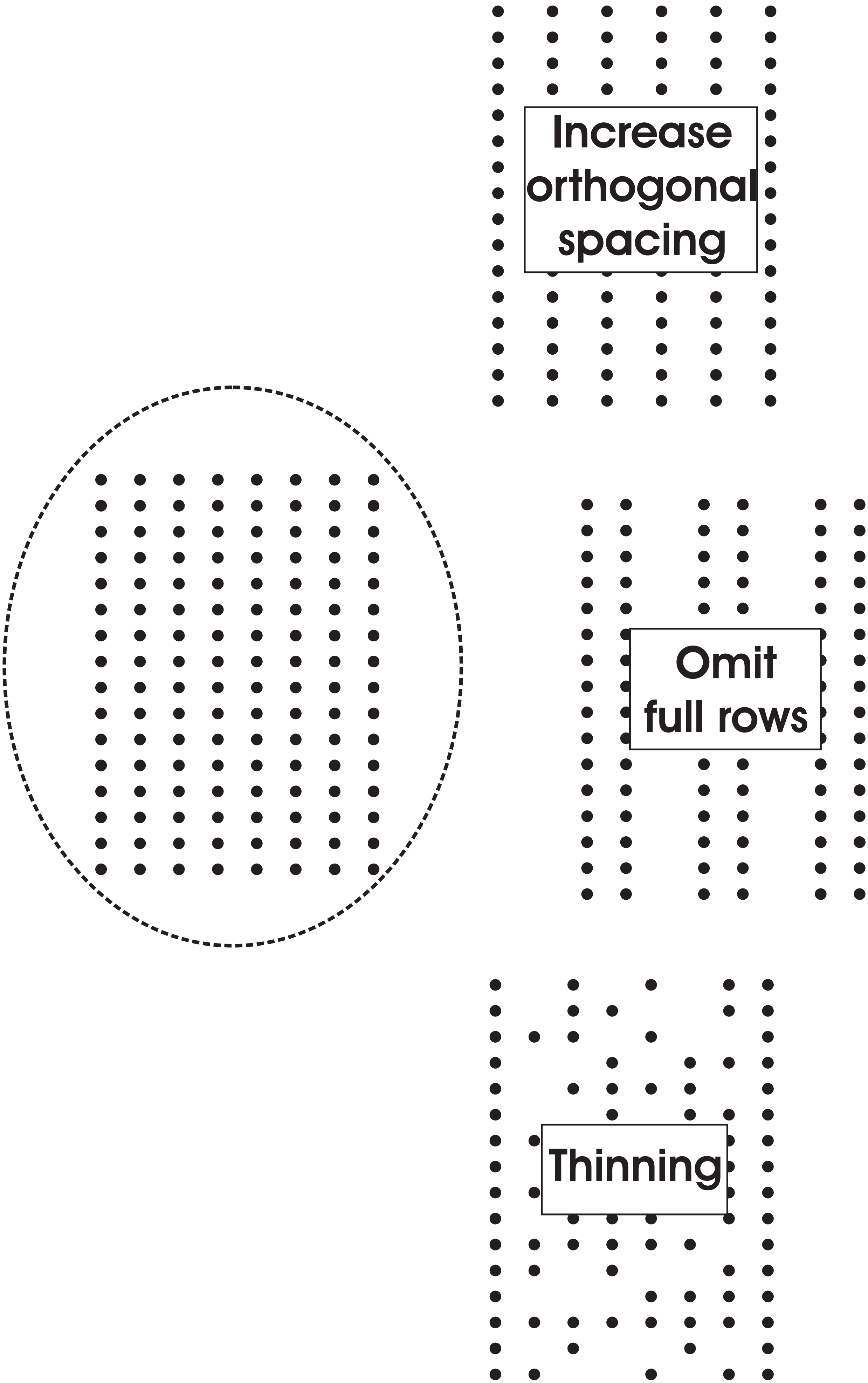


Table 1

x (m)	y (m)	trunk diameter d (cm)	$IL_{regular}$ (dBA)	IL_{random} (dBA)	trunk basal area
1	2	22	5.2	6.0 (0.1)	0.020
2	1	22	3.7	5.6 (0.1)	0.020
2	2	22	2.8	3.3 (0.3)	0.010
2	3	22	1.9	2.7 (0.5)	0.008
3	2	22	2.9	3.1 (0.6)	0.007
3	1	22	3.9	3.9 (0.2)	0.013
1	3	22	4.4	4.8 (0.1)	0.015
3	3	22	2.4	2.5 (0.2)	0.005
0.5	1	11	5.9	8.1 (0.1)	0.020
1	0.5	11	4.8	7.8 (0.1)	0.020
0.5	1	11		6.7[*] (0.2)	0.015
0.75	0.75	11	5.4		0.017
0.75	0.75	11		6.2[*] (0.3)	0.013
1	1	11	3.8	4.8 (0.1)	0.010
1	2	22	4.5[a]	5.8 (0.1)[a]	0.015
1	2	22	4.5[b]		0.015
1	2	22	4.9[c]	5.9 (0.3)[c]	0.015
1	2	22	4.6[d]		0.015
1	2	22	4.9[e]	6.2 (0.0)[e]	0.015
1	2	22	4.7[f]		0.015
1	2	22	4.7[g]		0.015